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A simple model to forecast wheat yield in Western Australia

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Abstract

Stress, defined as the lack of sufficient water to maintain maximum growth rates and yields, has long been recognized as a dominant factor in Australian wheat yield. Thus, by relating stress to crop yield and incorporating seasonal forecasts, a simple predictive crop model can be developed, the data requirements of which are commensurate with available meteorological seasonal forecasts. Such a model has been applied to the Merredin district of Western Australia and its potential is illustrated through the use of yield hindcasts for the 1984-1986 seasons.

Introduction

The growth and development of crops from sowing to harvest is influenced by a number of climatic and soil factors which interact in a very complex way. In recent years research has gone into the development of models to predict and simulate plant growth. Baier (1979) classified these crop-weather models into three broad categories: (i) crop growth simulation, (ii) crop-weather analysis, assessing crop response to weather and climate, and (iii) empirical-statistical models, where several weather variables are related to yields.

In Western Australian numerous studies have used the latter approach (Gentilli 1946, 1959; Fitzpatrick 1970; Hill & Goodchild 1981; Wigley & Tu Qipu 1983) to quantify the sensitivity of wheat yields to climate. They are particularly useful for zoning and mapping areas in terms of their suitability for growing crops and estimating yield potential. Nevertheless, statistical methods are limited for crop yield forecasting as they incorporate complex non-linear interactions between independent variables and there is no evidence to suggest normality of errors (Matis *et al* 1985). Baier (1977) and Hill & Goodchild (1981) noted interactions between weather and technology as well as weather variables themselves. Also, Hill & Goodchild (1981) found that long term historical data bases are likely to include unquantifiable historical events that have statistically intractable effects on yields.

A crop growth simulation model, adapted from CERES-Wheat (Ritchie & Otter 1985), has been developed for conditions at the Western Australian Department of Agriculture's Merredin Research Station (118.17°E, 31.29°S) in the eastern wheat belt of Western Australia (Perry 1986, pers comm). This model relies on a fallow-cereal crop water balance and computes soil water flow, crop growth and phenological development (McMahon 1983). Yield predictions can normally only be made at the end of the season and are sensitive to daily changes in temperature, rainfall and radiation. Duchon (1986) used such a model, CERES-Maize, to predict yield, using a combination of current weather, and sequences of past weather for the time between prediction and harvest. Application of this approach to Merredin yielded a low correlation between predicted and observed yields for past trials. This is a reflexion of the present inability to simulate accurately the plant-environment system on a daily basis, when significant biological events happen in much shorter time intervals, beyond the resolution of available standard meteorological data.

However, it is neither essential nor practical to model at a level greater than that required for useful predictions and the model sophistication should be commensurate with routinely available input data, such as meteorological forecasts. Simple models can have a powerful predictive value when one or two major factors dominate the performance system (Ritchie 1983). Stress, defined as the lack of sufficient water to maintain maximum growth rates and yields (Mederski 1983) has long been recognized as dominating the performance of Australian wheat (Nix & Fitzpatrick 1969). Accordingly, a simple crop-weather analysis model that relates stress to crop yield (Frere & Popov 1979) was adapted to the Merredin Research Station using results from a ten year direct drilling wheat trial (1977-86) (Jarvis *et al* 1986). Incorporation of meteorological seasonal forecasts into the model, meant that yield predictions were possible and this procedure is illustrated with hindcasts based on the seasonal forecasts issued for 1984-86.

Model Description

The crop-weather analysis model we used was originally designed by Frere & Popov (1979). It was designed to provide developing countries in semi-arid conditions with a simple technique for monitoring crop conditions, thereby allowing the preparation of quantitative yield assessments. As such it requires a minimum amount of actual data and calculations. Central to the method is the determination of the crop water balance which shows directly whether the crop is experiencing stress or not. An accumulated stress factor (stress index) is determined from the water balance and as the season progresses better reflects the ability of the crop to produce yields. Crop assessments are based on the past relationship between final stress indices and actual yields.

The basis of the model is a cumulative water balance which is summed for 10 day intervals over the whole growing season. This is done by adding the difference between precipitation received and water lost by evapotranspiration, to the existing stored moisture which is first estimated at the sowing date. A potential evapotranspiration (PET) is defined as the maximum quantity of water which may be evaporated by a uniform cover of dense short grass when the water supply to the soil is not limited (Penman 1948). When the available water supply can satisfy the PET rate, maximum growth is assumed to occur; but when it does not, stress is implied so that growth rates and final yields suffer. The stress factor gives a direct measure of the expected reduction in yield.

The only input data needed throughout the growing season is the actual precipitation (Pa) received in 10 day periods (decades), *ie* from days 1-10, 11-20, and from day 21 until the end of the month for each month. The last decades of some months have 11 days to ensure continuity of the monthly notation and the use of standard meteorological information. Rainfall is rounded to the nearest millimetre to eliminate small showers (< 0.6 mm) which are considered to have little significance, being evaporated rapidly in most conditions. Runoff is not accounted for since no measurements of this are routinely available.

The average daily PET for a given month was calculated from the Penman formula (Penman 1948) using climatological records of mean monthly temperature, relative humidity, pressure, sunshine duration and wind speed (Frere & Popov 1979). Estimation of total radiation can be found from direct observations or measurements of sunshine duration (*eg* Frere & Popov 1979; Edwards & Lyons 1982), whereas the remaining input data are estimated from standard climatological observations.

Mean monthly wind speed was estimated from the Merredin wind rose. Monthly values were found by multiplying the average of the mean 0900 and 1500 wind speeds with a ratio, determined from the ratio maps of Hutchinson *et al* (1984). In the absence of significant errors in the 0900 and 1500 records the estimates obtained are expected to be within 10% of the actual values (Hutchinson *et al* 1984).

Frere & Popov (1979) found that the Penman formula under-estimated evapotranspiration in dry environments by not accounting for dry air advection. To rectify this, they modified the Penman coefficient affecting the wind speed whenever the average minimum temperature was above 5 C and the difference between monthly average maximum and minimum temperatures was more than 12 C. For larger temperature differences, a larger value of the coefficient was used. Consequently, for Merredin the coefficient was modified for the warmer months of September through to April, utilizing values given by Frere & Popov (1979).

Monthly values of PET were obtained by multiplying the mean daily PET by the number of days for each respective month. These values were then divided into decadal periods by a simple mathematical procedure based on the curve fitted to the monthly values X_c, for $c = 1$ to 12. By representing the three decades for each month by Y_1, Y_2 and Y_3, their individual values are determined by the equations:

$$Y_2 = (X_c/3) \quad (1)$$
$$Y_1 = (X_c/3) - (X_c - X_{c-1})/9 \quad (2)$$
$$Y_3 = (X_c/3) + (X_{c+1} - X_c)/9 \quad (3)$$
$$\text{such that } X_c = Y_1 + Y_2 + Y_3 \quad (4)$$

The values for the three decades (Y_1, Y_2, Y_3) were adjusted so that the monthly total X_c is preserved. If the total of the three decades is less than X_c, 1mm is added to the decade Y_3 or Y_1, depending on whether the slope between X_c and X_{c+1}, increases or decreases from the previous monthly interval (X_{c-1} to X_c). Alternatively if the total is greater than X_c, 1mm is subtracted from Y_3 or Y_1, depending on whether the slope decreases or increases from the previous interval. When a point of inflexion occurs at a particular month, Y_2 is given the largest (or smallest) decadal value depending on whether the curve is convex or concave.

The water requirements of the crop are found by multiplying the decadal PET (E_T) with the respective crop coefficient (K_{cr}) for that period:

$$WR = E_T K_{cr} \quad (5)$$

Such an equation allows for the fact that cultivated crops pass through several stages from emergence until maturity. Over this period the plant cover varies in comparison to the reference short grass used in defining PET and this variation is expressed as the crop coefficient, being the ratio of maximum actual evapotranspiration over PET.

The total water requirements of a potential highest yielding crop are based on conditions experienced at the trial site during 1974, when yields reached maximum expected values of 3 tonne/ha (Jarvis 1987, pers comm). For that year, the sum of stored soil moisture at sowing, estimated from the water balance subroutine of CERES-Wheat (McMahon 1983), and rainfall during the growing season came to 280mm. Therefore it was assumed, that if this amount of moisture was available and evenly distributed to a crop, no stress would be incurred and maximum yields close to 3 tonne/ha would result. The most regularly used crop coefficients of Doorenbos & Pruitt (1977) were slightly increased so that when they were multiplied with the decadal PET values the total water requirement for the season came to 280mm. At the same time the distribution of the decadal water requirements was related to the observations of French & Schultz (1984) which showed that 70% of the total water use occurred by anthesis. At Merredin, anthesis usually occurs in mid-September and hence the crop coefficients were adjusted to ensure that 70% of the total water requirement was between sowing and anthesis. The relative proportions of the total water requirement were approximated as 0.3 for the period (c 2 months) between sowing and tillering, 0.4 for the period (c 2 months) between tillering and anthesis, 0.2 for the following month up to soft dough, and 0.1 for the remaining time to maturity.

The current readily available moisture, RS_i, is found from:

$$RS_i = RS_{i-1} + (Pa - WR) \quad (6)$$

where the difference between actual precipitation and crop water requirements is added to the existing stored water, RS_{i-1}. RS indicates the amount of usefully stored or readily available water in the soil, and this is commonly referred to as the water reserve between the field capacity and the permanent wilting point. The amount readily available depends on the depth of the soil exploited by the roots and the physio-chemical characteristics of the soil (Frere & Popov 1979). For the heavy, calcic red brown earth at Merredin, the maximum amount of stored moisture held in the 1.2 m depth rooting zone is 180 mm (Perry 1986 pers comm).

Originally designed for parts of Africa and Asia which experience a brief wet-season, this procedure assumes that there is no stored soil moisture before the first opening rain. Such an assumption cannot be applied to Western Australian conditions, where moisture is almost always carried through from either autumn or summer. Thus the validated water balance subroutine from CERES-Wheat (McMahon 1983), was used to estimate the stored moisture accumulated before the sowing date. The model was run with daily values of rainfall, radiation and temperature from the first of January through to the beginning of the 10 day period in which sowing occurred. Values of stored water determined varied from 0mm in 1985 to 64mm in 1984.

When the final stress factor was plotted against yield for the 10 years, two of the years, 1979 and 1984, heavily over-estimated the stress in comparison to the observed yield. However, the end of both 1978 and 1983 were very wet, suggesting that moisture could have been carried through from these years and this is not accounted for in initializing the soil moisture balance from January. By using the final soil moisture profile for the previous year to initialize the profile for the following year, very different soil moisture estimates were obtained for 1979 and 1984. For these two years the values increased from 53mm to 96mm and 64mm to 106mm respectively. Negligible increases of 1 to 4mm were found for the other years.

If RS is greater than the total possible stored water, in this case 180mm, a water surplus is registered and stress is assumed to occur. Likewise, if insufficient moisture is available to maintain maximum growth rates stress is also inferred. This is the case when RS becomes negative — a water deficit. As such, RS only relates what the available moisture content would be if a crop was to be growing at its potential rate not limited by stress. Because Merredin has a very high water holding capacity and a dry climate, only deficits were observed.

Stress is represented by a culminative stress index (I) and is calculated (for deficits, D) as:

$$I = I_{i-1} + (D/WRT) \quad (7)$$

where WRT represents the total water requirement for the growing season of the potential highest yielding crop, and I_{i-1} is the previous value of I. Expressed as a percentage, this factor indicates the extent to which the water requirements of a crop have been satisfied in a cumulative way up to that point in its development. At the beginning of the season, the index is given a value of 100. It will remain at that value for successive decades until a surplus or deficit appears. If a deficit of say 28mm appears, the quotient between 28 and 280 (the total water requirement) is 0.1. This corresponds to 10% of the water requirements not satisfied, so the index drops from 100 to 90. The calculation is continued through to maturity where the final stress index reflects the cumulative stress endured by the crop throughout the season. As such, it is usually closely linked with yield unless other harmful factors such as pests, diseases or frost have had an over-riding influence.

Results and Discussion

The accumulated stress-yield relationship for the 10 year direct drilling trial (Fig. 1) has a least squares regression of:

$$Y = 37.12\,I - 1083.58 \quad (8)$$

where Y is the expected yield in tonne/ha and I the accumulated stress over the growing season. The

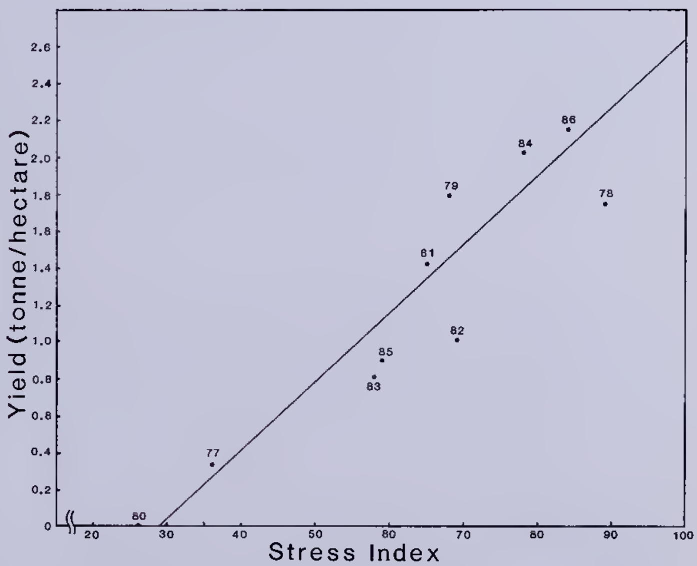

Figure 1 Comparison between yield and computed stress indices for the Merredin Research Station.

accompanying correlation coefficient is 0.94 ($r^2 = 0.88$) and is significant at $P = 0.001$. This illustrates that moisture stress is a significant yield determining variable for heavy soils in the Merredin district. The lower than expected yield in 1978 may have resulted from surface detention and evaporation of water due to poor soil structure at the start of the trial and the high rainfall (410 mm) in 1978 (Jarvis *et al* 1986). Equation (8) formed the basis of the predictive mode of the model.

Yield predictions made after the growing season but based on information available before the season are known as hindcasts. These were made by using decile rainfall corresponding to the seasonal forecasts issued by Austweather prior to the corresponding season. Such forecasts, based on large scale ocean-atmosphere indicators, endeavour to predict whether rainfall will be in one of three possible categories: (i) below normal (signifying the lower 30% of climate data), (ii) near normal (signifying the middle 40% of recorded values), or (iii) above normal (signifying the upper 30% of recordings).

Consistent with a similar decision-making model (Brown *et al* 1986), the three forecast categories were represented by the deciles 1.5, 5 (median), and 8.5 of the distribution of growing season precipitation. For certain situations, intermediate 2 event forecasts were made by Austweather and these were represented by decile 3 (for normal to below normal forecasts), and decile 7 (for normal to above normal forecasts), as these values are positioned at the boundaries between the two categories used in each respective 2 event forecast.

The hindcasts were first made for the beginning of the 10 day period in which sowing occurred and the initial soil moisture was estimated from CERES-Wheat. In place of actual rainfall, however, the decadal decile rainfall was used as an indicator of the distribution of the rainfall over the forecast period. Thus the level of sophistication of the climate data fits that of the seasonal forecasts. The monthly values were separated into 10 day intervals by the same mathematical procedure outlined in equations (1-4). Such a process was carried out for early winter (April-June), late winter (July-September) and early summer (October-December). Estimated stress was used to predict yield via equation (8).

An updated yield prediction followed at the end of June. Actual rainfall figures for June replaced the decile rainfall figures and another estimate was made. This updating continued until the end of the growing season when the final yield estimate was made. Initial and updated predictions for 1984-1986 are shown in Fig. 2.

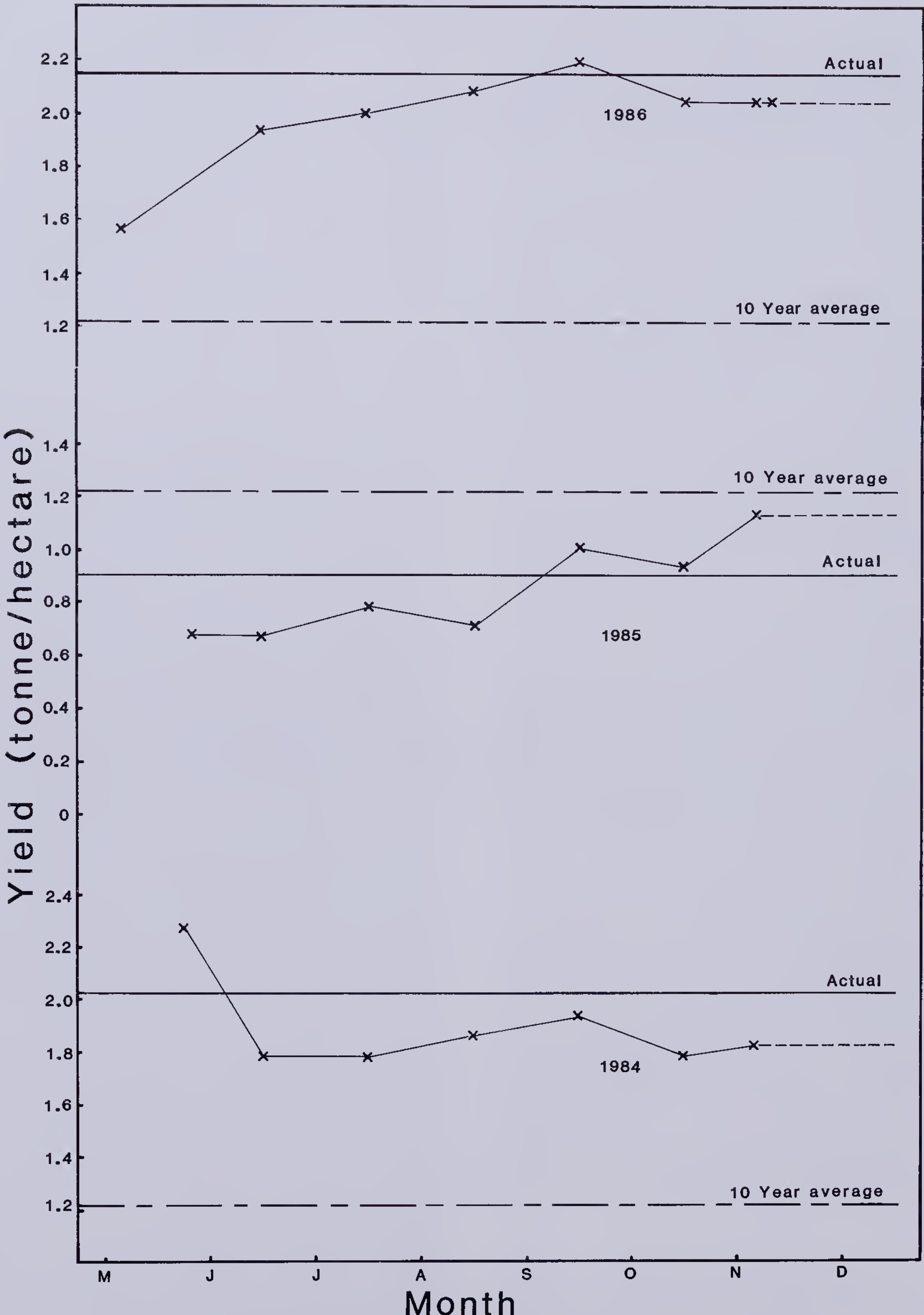

Figure 2 Yield predictions made at various stages during the growing seasons for 1984-1986 based on seasonal forecasts, compared with the 10 year average yield and the actual yield.

In 1986 the yield prediction gradually rose and levelled out near 2 tonne/ha. The rise in predicted yield was due to the actual rainfall being slightly wetter than the decile rainfall given by the seasonal forecasts. A similar result occurred for 1985 except that the predicted and actual yields were all about a tonne/ha lower.

In 1984 the reverse happened at the beginning of the season. An initial estimate of 2.26 tonne/ha declined to 1.78 tonne/ha at the end of June. This sudden change in yield estimate was essentially caused by the rigidness of the seasonal forecasts, individually restricted to a three month time-span. The outlook was for average to above average rainfall for the period April to June and below average rainfall from July through to September. What eventuated was an average to above average April and May, followed by below average rainfall for June, July and August. A rigid three month forecast could not account for such variation and thus the possibility of monthly forecasts is being considered.

Ultimately the value of the predicted yield is dependent on the stress/yield relationship and the accuracy of the seasonal forecasts. The relative success of the predictive model over the 1984-86 seasons is a direct function of the success of the input seasonal forecasts. Nevertheless, this simple model is commensurate with the available meteorological data and is able to express seasonal forecasts directly in terms of expected yield. The value of such predictions is not in the actual yield predicted, but rather as a comparative measure of how a particular year is expected to compare to previous years. At this stage, the model has only been applied to one soil type at one location. For other regions and soil types, different crop responses are expected but could easily be accounted for through modification of the maximum stored water and water required for maximum yield.

Conclusions

A crop-weather analysis model similar to Frere & Popov (1979) was developed and applied to the Merredin Research Station. By including soil moisture estimates at past sowing dates from CERES-Wheat, a correlation of 0.94 between yield and final stress was obtained. This strong relationship between stress and yield is in agreement with the observation of Nix & Fitzpatrick (1969) that lack of sufficient water to maintain maximum growth rates and yields is a dominant influence on Australian wheat. Such a relationship can be used to provide a direct link between expected seasonal weather conditions and yield as the data input required is of a similar sophistication to available seasonal forecasts. Hindcasts for the 1984-86 seasons illustrate the potential of the method as a basis for a dynamic decision making model.

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